U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-276 579

Subsidence and Related Effects on Wastewater Collection and Treatment Facilities

Houston-Galveston Area Council, Tex

Prepared for

Environmental Protection Agency, Washington, D C

Nov 76

PB 276 579

SUBSIDENCE
AND RELATED EFFECTS ON WASTEWATER COLLECTION AND TREATMENT FACILITIES

REPRODUCED BY
NATIONAL TECHNICAL
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U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

NOVEMBER 1976

HGAC HOUSTON-GALVESTON AREA COUNCIL

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SUBSIDENCE AND RELATED EFFECTS ON WASTEWATER COLLECTION AND TREATMENT FACILITIES

AREAWIDE WASTE TREATMENT MANAGEMENT PLAN
FOR THE
GREATER HOUSTON AREA
(SECTION 208, P.L. 92-500)

NOVEMBER, 1976

PREPARED FOR THE HOUSTON-GALVESTON AREA COUNCIL
BY THE GULF COAST WASTE DISPOSAL AUTHORITY

The preparation of this report was financed through a grant from the U.S. Environmental Protection Agency.

TABLE OF CONTENTS

I. Introduction ..... p. 1
Figure I - Land Surface Subsidence ..... p. 2

II. Synopsis of the Subsidence Phenomenon ..... p. 4
A. List of Recommendations for Subsidence Research Needs ..... p. 5
B. List of Recommendations for Subsidence Corrective Measures ..... p. 6

III. Impacts of Subsidence ..... p. 7

IV. Subsidence Mapping Procedure ..... p. 10

V. Identification of Subsidence Affected Areas and Domestic Waste Treatment Facilities ..... p. 13
Table I - Subsidence Affected or Potentially Affected Domestic Waste Treatment Facilities ..... p. 14
Inflow ..... p. 16
Tidal Flooding of Plant Sites ..... p. 17

VI. Effects of Subsided Wastewater Treatment Systems on Water Quality ..... p. 19
Table 2 - Subsidence Effect on Water Quality ..... p. 20

VII. Individual Summaries of Selected Subsidence Reports and Articles ..... p. 25
A. List of Summarized Documents ..... p. 25
B. Individual Summaries ..... p. 27
C. Recently Identified Studies ..... p. 53

VIII. Glossary ..... p. 54

IX. Map of Subsidence Affected Land Areas and Domestic Waste Treatment Plants ..... Attachment

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No. PB276579

4. Title and Subtitle
SUBSIDENCE AND RELATED EFFECTS ON WASTEWATER COLLECTION AND TREATMENT FACILITIES

5. Report Date
November 1976

6.

7. Author(s)
Gulf Coast Waste Disposal Authority

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Gulf Coast Waste Disposal Authority
910 Bay Area Blvd
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10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
Houston-Galveston Area Council
P. O. Box 22777
Houston, Tx 77027

13. Type of Report & Period Covered
Final

14.

15. Supplementary Notes

16. Abstracts

Addresses the impacts of subsidence on domestic facilities and collection systems. Industrial facilities are a unique problem. A technical input report to the Greater Houston Areawide Treatment Management Planning Program-208.

17. Key Words and Document Analysis. 17a. Descriptors

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 62
	20. Security Class (This Page UNCLASSIFIED	22. Price A04-A01

PART I - INTRODUCTION

Land-surface subsidence (Figure 1) is a physical process which causes a gradual regional sinking of the land. Subsidence influences wastewater treatment in three ways in the designated Houston section 208 area, including tidally induced inflow into sewage collection systems, tidal flooding at certain wastewater treatment plant sites, and an increased hurricane vulnerability.

Land-surface subsidence, as will be explained in Part II, results from the withdrawal of ground water at a rate faster than it can be recharged. This reduces water pressure in the water bearing sand and compactible clay formations (aquifers) which in turn causes water to be squeezed from compactible clays. As the clays compact, the land surface sinks.

The study of subsidence is a necessary part of Water Quality Management Planning because of its impacts on wastewater collection and treatment facilities. The study of these impacts is segregated into two categories, industrial and domestic, because each category has unique characteristics and because public ownership and control generally occurs in domestic facility operation.

This document addresses the impacts of subsidence on domestic facilities and collection systems. Industrial facilities are also affected. Houston Ship Channel industries have experienced treatment facility flooding problems as well as submergence of dockside pipelines and stormwater drainage systems. Industry is a unique case, however, in that as private entities, each is planning and implementing its own subsidence corrective measures. Usually these measures are implemented as part of the industries' facility improvement plans with the Environmental Protection Agency to achieve treatment levels dictated by the 1977 and 1983 goals.

Domestic facility improvements are more directly influenced by areawide planning because they are dependent upon public funding disbursed in response to areawide plan priorities.

This report reflects results and conclusions summarized from existing literature, including the twenty documents individually summarized in section VII, and others specifically referenced in this report.

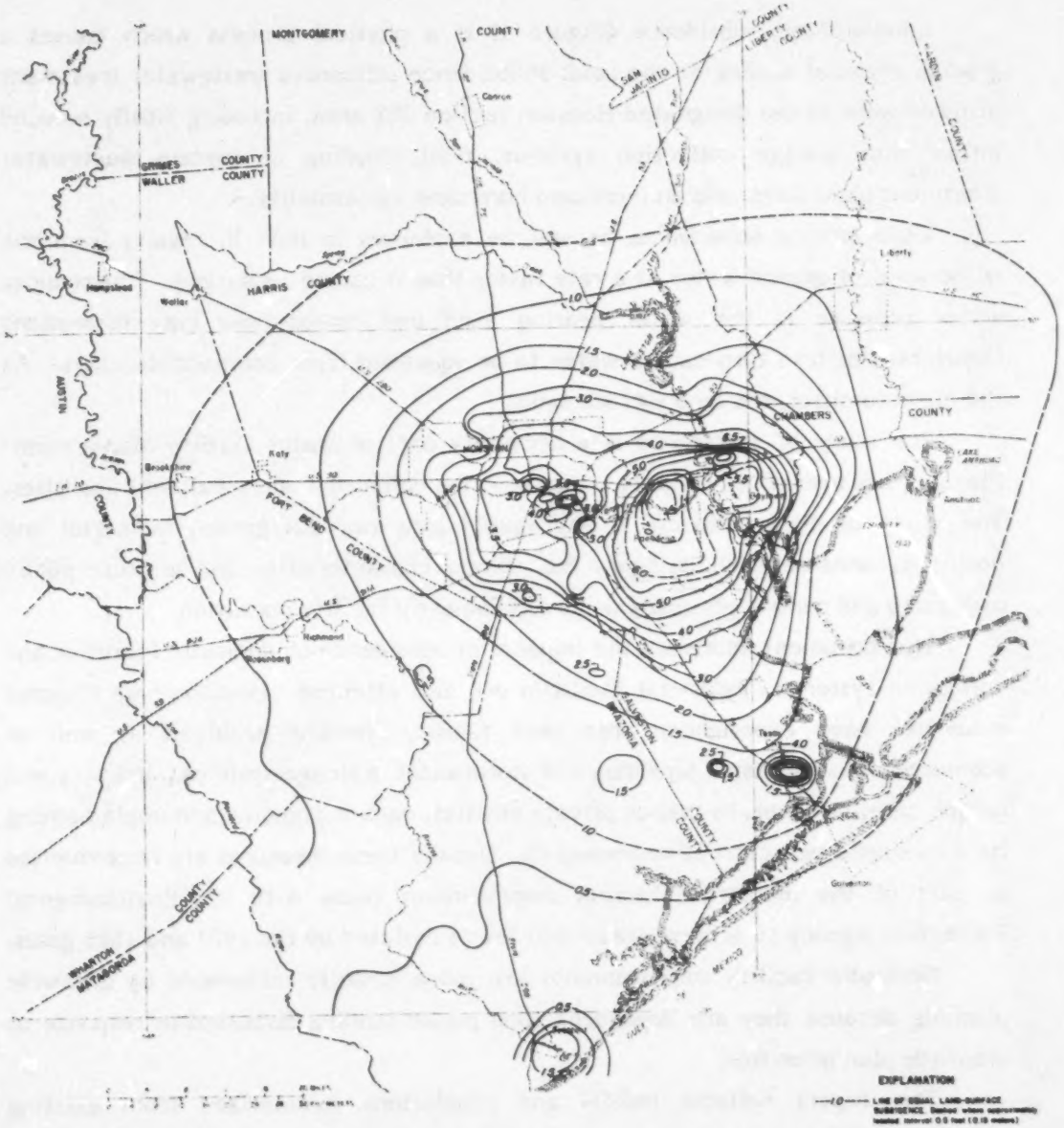

FIGURE 1

SUBSIDENCE OF THE LAND SURFACE, 1943-1973

FROM GABRYSCH, R.K. ET AL (SUMMARY 4)

Subsequent sections will discuss the subsidence phenomenon, identify the direct impacts of subsidence, discuss the methodology for identifying subsidence-affected wastewater treatment facilities, identify the effects of subsidence on treatment plants, identify the effects of subsided waste treatment plants on water quality, and summarize documents dealing with subsidence.

Subsidence has been recognized in the Houston area as a problem for more than twenty years, but surface water supply projects which would have alleviated the problem have always lagged behind water demand. Ground water withdrawal and consequential subsidence have continued to increase. The Coastal Industrial Water Authority (CIWA) project to bring Trinity River water to Houston Ship Channel industries and other users, and Houston's future plans to divert Lake Livingston water into the Lake Houston surface water supply should significantly reduce ground water withdrawal requirements and subsidence by the early 1980's.

In 1974 the Gulf Coast Waste Disposal Authority was directed by the 63rd Texas Legislature (H.B. 705) to study subsidence and prepare a report recommending a "course of action." The Authority prepared the report and submitted it in January 1975 to the 64th Legislature entitled, Land Subsidence in the Houston Gulf Coast Area. Two directives for future efforts were contained in that report.

1. Initiate comprehensive subsidence investigations so that the effect of the CIWA surface water change-over can be accurately defined, and an effective quantitative groundwater withdrawal policy can be established.
2. Establish a new regional agency to control subsidence in the Houston-Galveston area.

In 1975 the 64th Legislature passed H.B. 552 creating the Harris-Galveston Coastal Subsidence District. The District is directed by a 15 member, locally appointed Board, and has a present professional staff level of 14. This organization has initiated some of the background research recommended by the Gulf Coast Waste Disposal Authority and is implementing regional groundwater controls to stop subsidence. Other activites of the district include initiation of a regulatory program, designed to end subsidence in critical subsidence prone areas. Long-range programs include optimization of groundwater and surface water usage through regulatory permitting processes while eliminating subsidence in Harris and Galveston Counties. The District has recently adopted its regional plan, the Harris-Galveston Coastal Subsidence District, District Plan, July, 1976. This document can be requested from the District Office at P. O. Box 58847, Houston, Texas, 77058.

PART II - SYNOPSIS OF THE SUBSIDENCE PHENOMENON

Subsidence of the land surface in the Houston 208 area is the direct result of compacting clay layers in the substrata. Artesian pressure declines in the aquifers allow overburden pressure to squeeze water from the clays. These artesian pressure declines directly result from high volume well water withdrawals and, to a lesser extent, from oil and gas withdrawals.

High volume water withdrawals sufficient to reduce artesian pressure began around 1918 in the Pasadena area and subsidence probably began shortly after 1920.

The cone of subsidence in the 208 area is centered along the Houston Ship Channel in northern Pasadena where up to 8.2 feet of recorded subsidence has occurred. Roughly concentric rings of recorded subsidence of one or more feet extend outward from the center approximately 30 miles. This area includes most of the 208 study area and approximately 2,500 square miles of the greater Houston-Galveston area.

Several articles summarized in this chapter contain projections of ultimate subsidence. Speculative estimates project that "19 feet or more" of ultimate subsidence will occur at the center of the cone of subsidence. More conservative modeled projections estimate 11.4 to 15.1 feet of subsidence, depending on when artesian pressure declines cease. Significantly less subsidence has been projected for areas outside the Pasadena-Baytown area.

Damages claimed and substantiated in the 208 area as a result of subsidence include protrusion of well heads and tidal flooding of previously dry areas. The former is a minor problem as compared to the latter which has caused millions of dollars of property losses in the Greater Houston Area.

A cost estimation and projection study was performed by the Texas Water Resources Institute. The results of this study estimate that losses of 109.6 million dollars occurred prior to 1974 (losses corrected to 1973 dollars), and project that 63.5 million dollars in property will be lost if an additional five feet of subsidence occurs.

Subsidence is essentially irreversible. If artesian pressures were raised to their original levels, estimates of rebound potential of the clays are only 0 to 5% of ultimate subsidence (Fisher, 1973). Assuming 1) that 15 feet of ultimate subsidence occurred in northern Pasadena; 2) that pre-1920 artesian pressures in the aquifers were established; and 3) that a 5% rebound occurred, elevations would increase by only 0.75 foot.

Several recommendations were offered in the reports which are briefly listed below. These recommendations can generally be segregated into two categories: Subsidence Research Needs, and Subsidence Corrective Measures. Because these recommendations represent a historical period of more than ten years, several have been implemented or are being studied as parts of long term projects.

A. LIST OF RECOMMENDATIONS FOR SUBSIDENCE RESEARCH NEEDS*

1. Subsidence prediction needs refinement by analyzing thicker, undisturbed core samples from wells. This should more accurately define preconsolidation and compressibility. (Lockwood & Carothers, 1969) (Carothers & Newnam, 1958) (Lockwood, 1954)
2. Well logs must be properly collected and analyzed to accurately project subsidence. (Carothers & Newnam, 1958) (Lockwood, 1954)
3. Further research is needed to determine the relation between liquid limit, void ratio, and compression of clays. (Carothers & Newnam, 1958)
4. Determine the effectiveness of the aquicludes in inhibiting vertical transmission of water. (Carothers & Newnam, 1958)
5. The importance of secondary settling of clays (non-hydrodynamic compaction) should be defined. (Carothers & Newnam, 1958)
6. Define the relationship between surface faulting and subsidence. (Lockwood & Carothers, 1969)
7. Regular topographic releveling is essential to the development of accurate subsidence prediction. (Lockwood & Carothers, 1969) (Lockwood, 1954)
8. Forecast coastal flooding. (Lockwood & Carothers, 1969)

*These recommendations are being implemented as parts of on-going research projects.

B. LIST OF RECOMMENDATIONS FOR SUBSIDENCE CORRECTIVE MEASURES

1.* Establish a new agency for subsidence control in the Houston Gulf Coast area. (GCWDA, 1975)

2.* Develop a sophisticated model to predict rates of aquifer recharge for subsidence areas so that the maximum "acceptable" withdrawal rate can be established. (Warren, et al, 1974)

3. Stabilize artesian pressures. (Jenson, 1974)

4.* Convert to surface water in the high volume pumpage areas to reduce subsidence. (Marshall, 1973) (C.E.C.E.F. INQUIRY, 1972) (Lockwood, 1954)

5. Construct levees and backfill to protect subsided areas, and provide legislative appropriation to finance construction. (Jenson, 1974)

6.* Establish the feasibility of municipal wastewater reuse to reduce ground water demand. (C.E.C.E.F. INQUIRY, 1972)

7. Raise piezometric levels by injecting excess treated surface water at a rate of 800 MGD. (C.E.C.E.F. INQUIRY, 1972)

8.* Planners, designers, and constructors must recognize and account for the effects of subsidence in their professional efforts. (Lockwood, 1954)

9. Wells should be dispersed to reduce the combined affects of wells producing in the same area. (Lockwood, 1954)

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*These recommendations have been or are being implemented in on-going projects.

PART III - IMPACTS OF SUBSIDENCE

During the literature search for this document, four potential subsidence impacts to sewage collection and treatment systems were expressed. These included; 1) inflow due to tidal flooding of previously dry areas, 2) facility flooding due to tides, 3) trunkline loss of grade, and 4) line breakage.

Recent literature was studied to validate these impacts, and only inflow and tidal flooding were verified.

In the second chapter of Costs of Land Subsidence Due to Groundwater Withdrawals,
July, 1974, Warren et al. explains:

> "At the surface, physical effects of subsidence are largely dependent on the location. Contrary to what might be expected, almost no damages occur as a direct result of subsidence. There are a few isolated reports of damages to well casings, pipe lines, and other structures" (i.e., Texas City outside the 208 Area). "Some instances in which subsidence might have aggravated damages due primarily to surface faulting do exist, but generally, direct physical damage due to subsidence is slight.[1] Reports on subsidence in other areas (8)* and results of surveys and observations in the study area bear this out."

"[1]The subsiding area is also plagued by numerous surface 'faults' and any relationship between subsidence and faulting is yet to be conclusively determined."

"*8 Poland, J. F. and G. H. Davis, 'Subsidence of the Land Surface in the Tulare-Wasco (Delano) and Los Banos-Kettleman City area, San Joaquin Valley, California,' Transactions of American Geophysical Union, Volume 37, #3, p.p. 287-296."

The Research Report 1; Texas Gulf Coast Program, by the Rice Center for Community Design and Research contains a section on coastal subsidence which draws essentially the same conclusion discounting line breakage or loss of grade except in one area, Texas City, which "experienced this phenomenon earlier in the century, and is an isolated instance of this phenomenon." This report concludes that "it is unlikely that this disruption is likely to occur again."

An understanding of the regional nature of subsidence bears this out. Subsidence is generally a process which is widespread areally with insufficient differential subsidence occurring along the length of a single line to reduce its grade materially, or stress it to the point of breakage. For example, in the central cone of subsidence differentials of up to 0.5 foot per mile have occurred between 1943 and 1973. This is an incline change of 0.01 foot per 100 feet. An eight inch grade sewer line has a minimum design drop or incline of 0.33 foot per 100 feet (TSDH Proposed Design Criteria, 1976). Therefore, for an eight inch grade line layed directly opposite to the subsidence incline change in 1943, subsidence will have reduced its grade by 3%.

To reinforce these contentions, officials of the public works departments of Pasadena and Baytown were interviewed by telephone. In both cases the officials speculated that subsidence might be aggravating the problems of trunkline grade loss and breakage, but both considered this problem minor in comparison to design and construction errors, and surface faulting.

Speculation occurs throughout the literature which suggests that surface faulting in the Houston Area results from, or is aggravated by, subsidence. Additionally, recent studies cite circumstantial evidence which relates fault activation to changing stresses along the edge of the Gulf Coast geosyncline. (Research Report 1; Texas Gulf Coast Program, Rice Center for Community design and Research.) Ground water withdrawal is also cited but with reservations. "..it is not clearly known whether such a mechanism (ground water withdrawal) occurring in the top few hundred meters of the earth's crust is sufficient to trigger movement along a fault plane that may extend thousands of meters in depth."

A recent University of Texas, Bureau of Economic Geology publication by L. F. Brown et al, entitled Natural Hazards of the Coastal Zone discusses several possible causes for fault activation including "increasing overburden pressure" (ground water withdrawal), "oil and gas production", "differential consolidation of sediments" (subsidence), and "natural movement."

No quantitative estimate of the relative importance of any of the preceding possible causes for fault activation is given in any of the documents reviewed for this report.

However, several of the documents consistently implied that surface faulting is aggravated by groundwater withdrawal, the confirmed causative factor of subsidence. For this reason, and the fact that subsidence is listed as a possible contributing factor, surface faulting and subsidence may be related, but the extent of that relationship has not been conclusively demonstrated.

Surface faulting does present a potential threat to water quality in the Houston 208 Plan Area because of its effect on pipelines and other structures. Like subsidence, known active faults should be researched and their effects considered in facility planning efforts undertaken as part of the Houston Areawide Plan effort.

In light of the preceding discussion, surface faulting cannot, at this point, be considered a direct effect or impact of subsidence. To do so would be to unjustifiably subordinate an equally important geomorphic process which, like subsidence, has a major impact on areawide planning.

Tidal flooding of service areas and plant sites is a directly related subsidence impact in the Houston 208 Area. To assess this impact and identify affected areas and treatment plants the flood plain mapping procedure discussed in Part IV was developed.

PART IV - SUBSIDENCE MAPPING PROCEDURE

A mapping procedure was developed by the Gulf Coast Waste Disposal Authority for this project to identify land areas and domestic waste treatment systems which might be adversely influenced by subsidence. Other existing sources of information showing flood zones and/or topography were either not sufficiently detailed, or were not recent enough for direct application to this project.

Because tidally-induced inflow and plant site tidal flooding were the only directly reported subsidence-related problems affecting waste treatment plants, the mapping of subsidence-affected land areas and domestic waste treatment plants involved the identification and mapping of tidal flood-prone areas. From these maps, communities whose service areas or sewage plants had become partially inundated by regular flood tides could be identified.

The following mapping and sewage treatment plant identification procedures were used:

1. Prints of the most recently prepared USGS 7½' quadrangle topographic maps (quad sheets) were obtained.
2. The year of topographic data for each quad sheet was identified (for all quad sheets in the 208 area either 1953 or 1963 contour data was available).
3. Three isobaric maps showing recorded subsidence from 1954 through 1973 were obtained from the literature.

   Map 1. "Subsidence of the Land Surface, 1954-59" from: Land-surface Subsidence in the Houston-Galveston Region, Texas, Robert Gabrysch, U. S. Geological Survey, Open File Report, 1969 (page 9).

   Map 2. "Subsidence of the Land Surface, 1959-64" from: Ibid (page 10).

   Map 3. "Subsidence of the Land Surface 1964-73" from: Land-Surface Subsidence in the Houston-Galveston Region, Texas. R. K. Gabrysch and C. W. Bonnet, U. S. Geological Survey, Open File Report, 1974 (page 14).
4. Using these maps, topographic contours on the quad sheets in the region were "corrected" to 1974 levels by subtracting the subsidence recorded since the data of topographic leveling on the quad sheet. New levels for the topographic contours were recorded to the nearest 0.5 feet because isobaric contours on the subsidence maps did not coincide and more "accurate" estimates from the very small scale subsidence maps were not considered meaningful or justified.

5. Land area flooding resultant from the average annual high tide (3 feet) and average 5 year high tide (6 feet) was then interpreted and was shaded in on the quad sheets based on the "new" contour values. Storm tide data were obtained from Hurricane Surge Frequency Estimated for the Gulf Coast of Texas, B. R. Bodine, Technical Memo #26, U. S. Army Corps of Engineers, February 1969. The annual and 5 year high tides were selected for the following reasons:

The annual tide with attendant estuarine inflow/infiltration into affected sewage treatment plants will cause a significant plant upset. (Ref. Part III.) The increased flow will cause suspension of solids and overflows in clarifiers and settling ponds, and biological treatment may be inhibited by salt water. At the very least, bypasses will have to be opened at the plants allowing the release of raw sewage. In some cases, where bay-side plant sites have been lowered, sludge beds and other units are subject to flooding, and mechanical damages to pumps and electrical equipment have occurred. Additionally, roads could be washed out or damaged. Because of the problems, service areas and/or plants which were partially inundated by annual tides were considered "subsidence affected."

The 5-year high tide was identified for two reasons. A zone of potential subsidence effect is important. Tidal inundation on a 5-year interval is indicative of that potential. Also the 5-year storm surge is 6 feet above mean sea level. With subsidence still occurring in the 208 areas, future levelings might indicate that potentially affected plants are now regularly affected by flooding. Therefore, estimates of future effect can be made based on the 5-year flood area.

A longer frequency storm, for example a 100 year or 50 year hurricane, will have a devastating effect on waste treatment operations. The Texas Coastal and Marine Council estimates that an additional 70 square miles of coastal lands will be flooded if a 'Carla-like' storm makes land fall at Galveston. These considerations must be taken into account in designing and building new plants. However, all the plants in the coastal area will be affected to some degree by a 'Carla-like' storm.

Its zone of effect is so great and its impacts are so varied (i.e.; flooding, power loss, wind damage, etc.) that it does not provide a meaningful indicator of the operational effects of subsidence on wastewater collection and treatment.

6. Using 13-County Sewer Study municipal service area maps, service areas and plant sites partially inundated by the annual or 5-year flood tide were identified as affected or potentially affected respectively.

7. The following information was then transferred manually from the USGS quad sheets to 1" to 1 mile bluelines of the Houston 208 area:
   a. Annual flood area - Shaded in Red
   b. 5-year flood area - Shaded in Magenta
   c. Affected sewage teatment plants - Red ¼" dots
   d. Potentially affected sewage treatment plants - Green ¼" dots

8. The final maps were then labeled "Map of Subsidence-Affected Land Areas and Domestic Waste Treatment Plants" concluding the subsidence mapping exercise.

9. The master copy of this map is on file with the H-GAC. It will be reproduced for utilization in the subsequent tasks of this project and copies will be publicly available.

PART V - IDENTIFICATION OF SUBSIDENCE-AFFECTED AREAS AND DOMESTIC WASTE TREATMENT PLANTS

As discussed in the impacts section, only three types of subsidence impact, tidally induced inflow, plant site flooding, and increased hurricane vulnerability, can be directly attributed to subsidence.

The appended map of the Houston 208 area identifies nineteen communities whose plant sites or service areas are now inundated by tides as a result of subsidence. An additional five communties have been identified which are potentially subsidence-affected. The zone of increased hurricane vulnerability is documented in Natural Hazards of the Texas Coastal Zone. (U.T.BEG, 1974).

This list is corroborated by a listing prepared by the District 7 office of the Texas Water Quality Board (Mert Coloton to Ed Sargent 9/9/74), by discussions with facility planners at the Houston-Galveston Area Council, and by discussions with city engineers in affected areas. Subsequent discussion in this chapter is directed at aiding facility planners in defining the subsidiary problems of flooding and inflow at the following plants.

The attached table lists the subsidence affected plants and indicates the sources from which they were identified (Table I).

TABLE I.

SUBSIDENCE AFFECTED OR POTENTIALLY AFFECTED
DOMESTIC WASTE TREATMENT FACILITIES

DOMESTIC WASTE TREATMENT FACILITY & WCO	SOURCE OF IDENTIFICATION		NOTES
	Flood Map	TWQB List	
Bayview MUD 10770-01	Potential	Not listed	District official says tidal inflows are not a problem.
Galveston Co. WCID #1 Plant #1 10173-01	Affected	Not listed	District official says plant has not flooded since Carla. Inflow/infiltration occurs due to rainwater flooding.
Galveston Co. WCID #1 Plant #2 - 10173-01	Affected	Not listed	Never floods. Inflow/ infiltration occurs due to rainwater flooding.
Galveston Co. WCID #12 10029-01	Affected	Affected	Engineer indicated that tidal flooding quadruples the flow in the plant. The clarifier and the chlorine chamber also flood irregularly.
League City Main Plant 10568-01	Affected	Affected	Inflow/infiltration is no worse than in the 1960's. Plant has flooded so all motors and electrical equipment were moved up on roofs and rehoused.
League City - Glen Cove 10568-02	Affected	Affected	Glen Cove plant has not evidenced significant tidal inflow/infiltration.
San Leon - Under construction 11546-01	Affected	Non-existent	No contact made. Under construction.
Baytown - West Main 10395-02	Affected	Affected	Director of Public Works confirmed inflow problems.
Baytown - Lakewood 10395-05	Affected	Affected	Director of Public Works identified as worst hit by confirmed tidal inflow.
Baytown - East District 10395-07	Affected	Affected	Director of Public Works confirmed inflow problems.
Galena Park Plant #1 10831-01	Potential	Not listed	District official says tidal inflows are not a problem.

TABLE I.
(Cont'd.)

DOMESTIC WASTE TREATMENT FACILITY & WCO	SOURCE OF IDENTIFICATION		NOTES
	Flood Map	TWQB List	
Gulf Coast Waste Disposal Authority - Shoreacres 10758-01	Affected	Not listed	Engineer confirmed inflow/ infiltration problems.
Harris County FWSD #6 10184-01	Affected	Affected	H-GAC staff member said plant site regularly flooded.
Harris County WCID #1 10104-01	Affected	Affected	H-GAC staff member said plant site is irregularly flooded.
Harris County WCID #21 10105-01	Affected	Affected	District engineer says inflow due exclusively to rainwater run off.
Harris County WCID #84 10558-01	Potential	Not listed	District official says tidal inflows are not a problem.
Houston, Sims Bayou Plant - 10495-02	Affected	Not listed	Chlorine retention tank flooded during 6' tide. This has been corrected.
La Porte, Plant #1 10206-01	Potential	Not listed	District official says tidal inflows are not a problem.
Morgan's Point 10779-01	Potential	Not listed	District official says tidal inflows are not a problem.
Nassau Bay 10526-01	Affected	Affected	Inflow/infiltration is the big problem. Plant has not flooded since Carla.
Pasadena, Vince Bayou Plant 1-A - 10053-01	Affected	Not listed	Engineer confirms inflow/ infiltration problems.
Pasadena, Vince Bayou Plant 1-B - 10053-05	Affected	Not listed	Engineer confirms inflow/ infiltration problems.
Seabrook 10671-01	Affected	Affected	Plant formerly flooded but city has diked site. Inflow/ infiltration is big problem.
Texas Parks & Wildlife Dept. - Battleground Park STP - 11214-01	Affected	Affected	Official indicated that minor inflow problems have occurred. Future renovation is planned.

Inflow

Inflow due to tides is the greatest problem directly resultant from subsidence which impacts sewage treatment plant operation.

Of the 19 affected plants identified fifteen, Galveston Co. WCID #12 (Kemah), League City Main, League City Glen Cove, Baytown (all 3 plants), GCWDA Shoreacres, Harris Co. FWSD #6, Harris Co. WCID #1, Harris Co. WCID #21, Nassau Bay, Pasadena Vince Bayou (2 plants), Seabrook and Battleground Park, experienced at least some tidally induced inflow. Kemah may be the most significantly impacted with wet weather and high tide influent flows more than four times what their normal per capita flows should be.

Inflow by tidal action produces the following impacts in varying degrees.

1. It increases lift station and pumping operation, thus reducing equipment life and increasing power consumption.
2. It decreases the effectiveness of settling processes like clarifiers because of increased flows. Tidally induced inflow can be so great in fact that no settling occurs.

   The City of Seabrook has identified a unique problem in this regard. Due to some chemical reaction, presumably induced by estuarine inflows, flocculation occurs and the floc produced has a neutral buoyancy.

   Conventional floccing agents are largely ineffective in sinking these particulates and Texas A & M University researchers are presently being consulted to find a solution to this problem.
3. Inflow reduces the effectiveness of all other treatment units by reducing retention time in the various processes. For example, the City of Kemah during high flows passes essentially raw sewage because retention times in the plant are less than one fourth what they should be. Kemah's problem is interesting as well because their effluent quality by conventional concentration testing (i.e., BOD_5 and TSS) is sometimes acceptable because the sewage is so dilute.

4. Inflow of estuarine water can inhibit biological processes. Several of the affected plants are located on or near estuaries where salt water ranges of 5 to 20 parts/thousand occur. Several of the severely affected plants like Kemah and Seabrook do not exhibit this problem because their biological process units are so regularly affected that they are acclimated. However, some of the engineers contacted have speculated that an estuarine inflow into a plant not acclimated to salt water would inhibit biological processes and reduce facility effectiveness. This speculation has not been confirmed in the study area however.

Tidal Flooding of Plant Sites

Discussions with plant engineers and/or H-GAC personnel concerning in-plant effects of subsidence identified at least 7 plants whose flooding has occurred or occurs frequently at the site. These include Galveston Co. WCID #12, League City Main, Baytown Lakewood, Harris Co. FWSD #6, Harris Co. WCID #1, Houston Sims Bayou, and Seabrook. Of these Seabrook, Houston Sims Bayou and League City Main have accomplished remedial construction which alleviates at least temporarily their plant site flooding problems.

Galveston County WCID #12 (Kemah) is partially flooded one or more times annually by tides. The units affected include the clarifier and chlorine contact chamber. Kemah is presently petitioning the TWQB to improve their position on the Federal Grant funding priority list. The City has long term plans which include abandonment of their present site for one with a higher elevation.

The League City Main Plant was flooded in 1972 during a 6 foot tide. Most of the electrical equipment and connections were ruined by this event and the City subsequently moved and rehoused all electrical equipment on the roofs of buildings and units at the plant site. The City engineer is satisfied that this is sufficient at the present time to protect his plant site from tidal events less significant than a full fledged hurricane.

The Baytown Lakewood plant site was also partially flooded during the 1972 six foot tide. The city has recently initiated a detailed plan effort for this system which will be finalized in September, 1976. The plan will specify the remedial action which will be implemented over the next two and one-half years.

The Harris County FWSD #6 plant located on the Houston Ship Channel has been identified by HGAC staff as "regularly flooded." The district engineer was contacted and stated that the entire unit, a contact aeration plant, is regularly inundated. He said the district has almost completed step 2 of their 201 facility plan which calls for relocation of the site.

The Harris County WCID #1 plant site is irregularly flooded by high tides. The district engineer indicated that flooding was not a problem and that only the chlorine contact chamber was affected.

The Harris County WCID #21 plant site was partially flooded in 1972 by a six foot tide. The chlorine contact chamber and some of the drying beds were flooded. This district is in the process of securing a Federal Grant for plant site and collection system improvement.

The Houston Sims Bayou Plant was partially flooded in the 1972 six foot flood tide. The chlorine contact chamber was affected. Subsequent to that time the unit had been elevated to eliminate this problem.

Seabrook's municipal facility is located on a tidal inlet of Galveston Bay. The plant has flooded in the recent past and remedial actions have been implemented. Several levees have been built around the treatment units using air dried, digested sludge which protects them from tides of approximately 4 feet. Long-range plans include the relocation of the Seabrook facility to higher ground.

PART VI - EFFECTS OF SUBSIDED WASTEWATER TREATMENT SYSTEMS ON WATER QUALITY

Generally the effects of subsided treatment plants on water quality involve increases in organic and nutrient loads and coliform bacteria contamination resultant from reduced wastewater treatment plant efficiency.

The potential for other subsidence effects on water quality is anticipated to increase as more land is subjected to the influence of tidal action.

Ten segments may be affected in this manner by the 24 affected or potentially affected treatment plants identified in this study. Table II identifies each segment and contains comments on possible types of impact. Each is discussed below.

Segment 0901 - Cedar Bayou Tidal.

The Baytown East District Plant is the only 208 area plant on this segment identified as affected by subsidence. Inflows to the collection system were identified by the Director of Public Works as a problem. Plant site flooding is not a factor.

Because no significant deviations from the Water Quality Standards were observed in this segment, the effect of subsidence on water quality is considered minor. The plant did by-pass significant volumes of sewage in the last quarter of 1974 and their average flows were almost twice their permitted volume. The percentage of this extra flow caused by subsidence induced tidal inflows is unknown however, and the plant is presently being expanded to 3 MGD. (Data from TWQB, Wastewater Effluent Report, 11/24/75.)

Segment 1001 - Tidal San Jacinto River.

Harris County WCID #1 Highlands discharges into this segment. The plant has a significant inflow problem, and the plant site is irregularly flooded. The plant reported by-passing sewage for 40 days between 9/74 and 8/75. Additionally, average flows from this plant have consistently exceeded its permitted volume. For these reasons the plant contributes significantly to the municipal loads in this segment. However, the segment has not evidenced significant deviations from its water quality standards in recent years and the TWQB has recognized its use as a contact recreation area.* Therefore, the segment seems presently capable of assimilating the extra load resultant from subsidence impact. (Data from TWQB Wastewater Effluent Report, 11/24/75.)

*Addendum #1 to "Water Quality Standards", November 26, 1974.

TABLE II

SUMMARY OF PLANTS AFFECTING WATER QUALITY DUE TO SUBSIDENCE

Segment Number	Segment Name	Affected Plant	Problem Inflow	Problem Site Flooding
0901	Cedar Bayou Tidal	Baytown East District 10395-07	Yes	No
1001	San Jacinto River, Lake Houston Dam to 200 yds below I-10 Bridge	Harris Co. WCID #1 Highlands, 10104-01	Yes	Yes
1005	Houston Ship Channel, Mouth of San Jacinto River to Morgan's Point	Morgan's Point 10779-01	Potential	
1006	Houston Ship Channel, 200 yds below I-10 Bridge to Turning Basin	1) Harris Co. FWSD #6, 10184-01	Yes	Yes
		2) Harris Co. WCID #21, 10105-01	Yes	Yes
		3) Harris Co. WCID #84, 10558-01	Potential	
		4) Houston Sims Bayou Plant, 10495-02	No	Yes
		5) Pasadena Vince Bayou 1-A, 10053-01	Yes	No
		6) Pasadena Vince Bayou 1-B, 10053-02	Yes	No
		7) Texas Parks & Wildlife Dept. Battleground S.T.P. 11214-01	Yes	Yes
		8) Galena Park S.T.P. 10831-01	Potential	
1101	Clear Creek Tidal	1) Nassau Bay 10526-01	Yes	No
		2) League City Main Plant, 10568-01	Yes	Yes

TABLE II
(Cont'd)

Segment Number	Segment Name	Affected Plant	Problem Inflow	Problem Site Flooding
1103	Dickinson Bayou Tidal	1) Galveston Co. WCID #1, 10173-01	Yes	No
		2) Galveston Co. WCID #1, 10173-02	Yes	No
2421	Galveston Bay	1) La Porte Plant #1 10206-01	Yes	No
		2) Seabrook 10671-01	Yes	Yes
		3) Bayview MUD 10770-01	Potential	
		4) San Leon MUD 11546	Yes	No
2425	Clear Lake	1) Gulf Coast Waste Disposal Authority Shoreacres, 10758-01	Yes	No
		2) Galveston Co. WCID #12 (Kemah) 10029-01	Yes	Yes
		3) League City Glen Cove, 10568-01	Yes	No
2426	Tabbs Bay	Baytown West Main Plant, 10395-02	Yes	No
2430	Burnett Bay	Baytown Lakewood Plant, 10395-05	Yes	Yes

Segment 1005 - Houston Ship Channel, Mouth of San Jacinto River to Morgan's Point.

The city of Morgan's Point is the only potential contributor of subsidence induced loads to this segment. Because the plant has reported no deviations from its BOD_5, TSS, and average flow requirements, the effects on this segment are negligible.

Segment 1006 - Houston Ship Channel, Turning Basin to 200 yards below the I-10 Bridge.

Six plants along this segment have been identified as subsidence affected. These include; Harris Co. FWSD #6, Harris Co. WCID #21, Houston Sims Bayou, Pasadena Vince Bayou 1-A, Pasadena Vince Bayou 1-B, and Battleground S.T.P. Two plants which exhibit potential effect are Galena Park S.T.P. and Harris Co. WCID #84.

Of the six affected plants, the largest, Houston Sims Bayou, has remedied its plant site flooding problems and is no longer considered a contributor to subsidence impact. The remaining plants exhibit problems associated with subsidence impact. Harris Co. FWSD #6 is reported to be regularly flooded and has reported average flow volumes more than twice their permitted level. This plant has also reported significant deviations from its permitted BOD_5 and TSS concentrations. The total flow of this plant is small at approximately 0.130 MGD.

Harris Co. WCID #21 has reported no significant deviations from their permit requirements. The collection system has a significant inflow/infiltration problem but a recent study eliminated tidal inflows as a contributing factor. The plant site was partially flooded in 1972.

Battleground S.T.P. is regularly flooded and has inflow problems. However, this is a very small plant which services only the San Jacinto Battleground Park facilities.

The two Pasadena Vince Bayou Plants are reported to have significant inflow problems. However, comparisons of flood areas to service areas indicate that there are only a few bayous in the service area which are tidally flooded. A significant portion of the inflow problem reported at these plants is rainwater run off inflow/infiltration and not subsidence induced tidal inflows.

Because of the other significant water quality problems and known causes evidenced in this segment, subsidence induced loading is probably a minor contributor to the problem.

Segment 1101 - Clear Creek Tidal.

The City of Nassau Bay and the League City Main Plant discharge into this segment. Both cities when contacted indicated they were presently coping with subsidence-induced inflow and plant site flooding problems. Neither plant has reported any deviations from permit values in average flow, BOD_5, or TSS concentrations. These data indicate that subsidence-induced problems at these plants are not adversely affecting water quality in this segment.

Segment 1103 - Dickinson Bayou Tidal

Galveston County WCID #1 has two plants which discharge into this segment. Although the mapping procedure indicated that portions of this district's service areas were tidally flooded, contact with the district engineer indicated that tidally induced inflow is not a problem at either plant. Because neither plant has reported any significant deviations from their permit requirements, the potential of subsidence-induced impact on this segment is slight.

Segment 2421 - Galveston Bay.

Of the three affected or potentially affected 208 area plants discharging into this segment, only the City of Seabrook is a recognizable contributor. The other two, Bayview MUD and San Leon MUD, are not contributing subsidence induced loads. Seabrook has reduced the threat of plant site flooding (Pg. 19) but does contribute to this segment's loading as a result of severe tidal inflow problems. The City treats the extra flow to a quality better than their permit requirement.

Segment 2425 - Clear Lake.

Clear Lake has a very stringent set of standards because of a long history of water quality problems and because of its continuing use as a recreational area. Three subsidence affected plants, GCWDA Shoreacres, Galveston Co. WCID #12 (Kemah), and League City Glen Cove discharge into this segment. Both Glen Cove and Shoreacres exhibit minor problems with inflow resultant from tides but Kemah's problems are significant. This district reported by-passing sewage 17 days between 9/74 and 8/75 and has reported some BOD_5 and TSS values in excess of their permit requirement. Contact with the district engineer yielded information that during high tide and wet weather conditions inflow to the plant exceeds 4 times its normal per capita flow. Most of this flow is run through the plant but

very little treatment is achieved because retention times are so short. The district is trying to secure federal funds to begin correction of this problem. The effect on the water quality of Clear Lake is indeterminable but subsidence impacts probably represent only a small load addition to the total permitted and uncontrolled loads in this segment.

Segment 2426 - Tabbs Bay.

Baytown's West Main plant is the only municipal discharger into this segment. The Director of Public Works confirms inflow problems but did not identify any plant site tidal flooding. The plant generally ran within its permit requirements during 1975 with one exception, which was not subsidence related.

Segment 2430 - Burnett Bay.

Baytown's Lakewood plant discharges into this segment and has confirmed inflow problems due to normal tides. The plant by-passed sewage on a regular basis. Average flow also exceeded permitted values for 8 of the 12 months reported. The quantitative affect of inflows on this segment is unknown.

The Brownwood subdivision has severe tidal flooding problems resultant from subsidence. This is the most significant contributor to the Baytown Lakewood plant problems.

PART VII - INDIVIDUAL SUMMARIES OF SELECTED SUBSIDENCE REPORTS AND ARTICLES

The following summaries of reports and articles are provided to assist in the understanding of subsidence, and to supplement point source facilities studies and other aspects of the Houston Areawide Plan. Narratives on each report are provided along with the original abstracts if available. Findings, summaries and conclusions are included verbatim in this chapter or are summarized depending upon their length.

A. LIST OF SUMMARIZED DOCUMENTS

The following documents are summarized in reverse chronological order:

1. Land Subsidence in the Houston Gulf Coast Area. Gulf Coast Waste Disposal Authority, January, 1975.
2. "Houston Land Surface Subsidence", Owen F. Jenson, The Slide Rule, December, 1974.
3. Land-Surface Subsidence in the Area of Burnett, Scott and Crystal Bays Near Baytown, Texas, R. K. Gabrysch and C. W. Bonnet, U. S. Geological Survey Water Resources Investigations 21-74, September, 1974.
4. Land-Surface Subsidence in the Houston-Galveston Region, Texas, Robert K. Gabrysch and C. W. Bonnet, U. S. Geological Survey, Open File Report, 1974.
5. Technological Limitations to Ground-Water Management, William F. Guyton Presentation: Water for Texas Conference, September, 1974.
6. Costs of Land Subsidence Due to Groundwater Withdrawal. John P. Warren, Lonnie L. Jones, et al, Technical Report No. 57, Texas Water Resources Institute, Texas A & M University, July, 1974.
7. An Analysis of the Rate of Decline in Groundwater Level in the Area of Houston, Harris County, Texas. (Masters Thesis) John G. Musgrove, University of Houston, Unpublished, December, 1973.

8. "Results of Land Survey of Houston-Galveston Area Announced; Land Sinking of Eight Feet Reported", U. S. Department of Commerce News Release, July 26, 1973.

9. "Sea Rising More Rapidly Along Texas and Louisiana Coasts; Land Sinking", U. S. Department of Commerce News Release, May 25, 1973.

10. Land-Surface Subsidence in the Texas Coastal Zone, W. L. Fisher, Bureau of Economic Geology, University of Texas at Austin, February, 1973.

11. "How Much More Will Houston Sink", A. Frank Marshall, Jr., The Slide Rule, February, 1973.

12. Inquiry on Land Subsidence and Wastewater Reuse. Citizen's Environmental Coalition, July, 1972.

13. Groundwater Conditions in the Galveston Bay Area - Harris, Galveston, and Chambers Counties, Texas. William F. Guyton and Associates, Texas Water Quality Board, February, 1972.

14. Land-Surface Subsidence in the Houston-Galveston Region, Texas, Robert K. Gabrysch, U. S. Geological Survey, 1969.

15. "San Jacinto Monument's Warning of Future Land Subsidence", Mason G. Lockwood and H. P. Carothers, Southwest Water Works Journal, January, 1969.

16. "Relation of Land Subsidence to Groundwater Withdrawals in the Upper Gulf Coast Region, Texas", A. G. Winslow and Leonard A. Wood, Mining Engineering, October, 1959.

17. Earth Subsidence Forecast from Tests of Deep Soil Samples. H. P. Carothers and Frank P. Newnam, Jr., Report Presented at American Society of Civil Engineers Spring Meeting - Texas Section, Beaumont, Texas, Soil Mechanics and Foundations Group, May, 1958.

18. "Land-Surface Subsidence and Its Relation to the Withdrawal of Groundwater in the Houston-Galveston Region, Texas", A. G. Winslow & W. W. Doyal, Economic Geology, Volume 49, No. 4, 1954.

19. Subsidence from Declining Artesian Pressure Can No Longer Be Ignored in Houston Area, Texas, Mason G. Lockwood, Texas Section A.S.C.E., April, 1954.

20. "Ground Waters of the Houston-Galveston Area". Margret D. Foster, Industrial and Engineering Chemistry, Volume 31, No. 8. August, 1939.

B. INDIVIDUAL SUMMARIES

SUMMARY #1

Land Subsidence in the Houston Gulf Coast Area, Gulf Coast Waste Disposal Authority, January, 1975.

Discussion:

The 63rd Legislature authorized the Gulf Coast Waste Disposal Authority in (HB705) to study subsidence and recommend a course of action. No funds were appropriated for this effort and the Authority completed a preliminary report which recommended two actions to be taken by the 64th Legislature.

"1) Establish an emergency appropriation of Eight Hundred Seventy One Thousand Seven Hundred and Twenty dollars ($871,720) for the GCWDA to carry out their assignment in accordance with H.B. 705."

"2) Establish a new agency to control subsidence in the Houston Gulf Coast Area to carry out an ongoing process of subsidence control."

The first action will allow for the development of a proper data base on groundwater withdrawal and related subsidence prior to the change to Coastal Industrial Water Authority (CIWA) surface water by many groundwater users in 1976.

The initial program proposed by the Authority may then be followed by an ongoing effort which will entail monitoring, subsidence analysis, water supply and demand analysis and related distribution, groundwater analysis, economic evaluation and the development of a technical subsidence control policy.

The report presents a detailed discussion of research needs, schedule of operation consultant requirements and funding for the first phase of the program. The program is divided into six activity series as follows.

1. Monitoring Program - This program would be designed to assess the adjustment of the aquifer to reduce groundwater withdrawal after 1976. Test wells would be drilled and well logs, water quality measurements and extensometer measurements would be collected to provide a data base for continuing aquifer evaluation.
2. Subsidence Analysis - This program will estimate projected subsidence in critical lowland areas and define immediate remedial programs to be undertaken by the new agency (Subsidence District). Subsequent refinement of subsidence prediction might modify these stop-gap type of measures.
3. Water Supply, Demand and Redistribution - This effort will be directed at assessing groundwater demand and relating that to future demand and new water supply schemes in order to minimize economic impact and maximize subsidence controls.
4. Groundwater Analysis - This effort will be directed at predicting recharge and future groundwater levels based on reduced groundwater use.
5. Economic Evaluation - This effort will continue the analysis of costs incurred as a result of subsidence.
6. Subsidence Control Manual - The purpose of this task will be to correlate the results of the previous tasks and produce an operational manual from which policy decisions can be made. The task will outline the ongoing research program necessary to facilitate the control efforts of the new subsidence control agency.

The report also delves into the processes of subsidence and identifies existing literature on the subject. Sixty seven articles, reports and other documents are listed.

The report does not address the organization of the subsidence control agency which is recommended because this is a public policy matter to be undertaken "by the able work of the mayor's and councilman's subsidence committee in preparation for the 64th Legislature."

SUMMARY #2

"Houston Land Surface Subsidence", Owen F. Jenson, Jr., The Slide Rule, December, 1974.

Discussion:

The report contained in The Slide Rule is itself a summary of Mr. Jenson's presentation to the Lone Star Water Well Association's Quarterly Board Meeting. Mr. Jenson's opinions and recommendations include:

1. Construction of levees and backfilling to protect endangered areas.
2. Legislative appropriations to finance construction activities.
3. Expansion of research to accurately define the problem.
4. Stabilizing artesian pressure by controlling pumpage in critical areas.

SUMMARY #3

Land Surface Subsidence in the Area of Burnett, Scott and Crystal Bays Near Baytown, Robert K. Gabrysch and C. W. Bonnet, U. S. Geological Survey, September, 1974.

Discussion:

This report and its predecessors, Land-Surface Subsidence in the Houston-Galveston Region, Texas (1970), and Preliminary Report on Land-Surface Subsidence in the Area of Burnett, Scott and Crystal Bays Near Baytown, Texas (1973) by Mr. Robert Gabrysch, et al, have been utilized in subsidence research more than the other reports summarized in this catalogue. The report contains more comprehensive analyses than other reports and its projection model addresses more variables than any of the other projection models developed to date. The model generally agrees with observed subsidence in the study area. The subsidence projections based on declining groundwater pressures generally follow the observed subsidence in the Texas City area and in a California study.

Several assumptions were made which deserve note:

1. The altitude of the potentiometric surface in 1920 was assumed to be the same as the original surface in 1890, and no subsidence occurred before 1920.

2. Artesian-head declines in the Alta Loma sand and Evangeline aquifer will continue at a rate of 6 feet per year until 1980. Thereafter no further head declines will occur. (Case I)
3. Artesian-head declines in the Alta Loma sand will continue at a rate of 6 feet per year until 1980 and at a constant rate until the potentiometric surface reaches the top of the Alta Loma sand in 1995. Thereafter, no further head declines will occur and the artesian heads in the Evangeline aquifer will continue to decline at a rate of 6 feet per year from 1970 to 1995, and then cease. (Case II)
4. Hydraulic pressure readings at various depths are assumed to be accurate.
5. Electric logs and micrologs of wells are assumed to accurately define the number and thicknesses of the clay layers in the sediments.
6. Compaction below 2,500 feet is negligible.
7. Undisturbed clay samples taken from test wells exhibited the same characteristics (primarily consolidation) in the lab as they would in the field.
8. Clay samples accurately characterize the clays underlying the study area.
9. Secondary effects (i.e., non-hydrodynamic compaction) were assumed to be minor.

Justifications were given for non-arbitrary assumptions (#4-9) either by logical subjective arguments or circumstantial evidence. It should also be noted that to a large extent the projections agree with historic subsidence patterns in other areas. The results from the same formula applied to historic data also track well with the past observed subsidence in the study area.

Abstract:

"Removal of water, oil, and gas from the subsurface in Harris County has caused declines in fluid pressures, which in turn have resulted in subsidence of the land surface. Subsidence in the area of Burnett, Scott, and Crystal Bays near Baytown is becoming critical because much of the area is now subject to inundation by high tides.

"Production of oil and gas from the Goose Creek Field on the southeast edge of Baytown had caused as much as 3.25 feet (1 meter) of subsidence by 1925. The subsidence due to oil and gas production is restricted to the area of production and has not extended to the area of Burnett, Scott, and Crystal Bays.

"Withdrawals of water from large-capacity industrial wells, which resulted in declines in artesian pressure, began about 1918. As much as 280 feet (85.3 meters) of artesian-head decline has occurred in the Evangeline aquifer, and as much as 320 feet (97.5 meters) of artesian-head decline has occurred in Alta Loma Sand of Rose (1943). Significant subsidence of the land surface probably began about 1920 or later and as much as 8.2 feet (2.5 meters) of subsidence had occurred in the area by 1973.

"The study of subsidence in the area of the three bays included the collection of undisturbed clay samples for laboratory analyses, collection of water-level records, and installation and monitoring of pressure transducers in clays and of observation wells in sands.

"Probable future subsidence was calculated for two loading situations. Case I provided that the artesian head in both the Alta Loma Sand and Evangeline aquifer would continue to decline at a rate of 6 feet (1.8 meters) per year until about 1995, when the potentiometric surface would reach the top of the Alta Loma Sand. The artesian head in the Evangeline aquifer would also decline about 6 feet (1.8 meters) per year until 1995.

"The ultimate subsidence expected for the assumed conditions of Case I and Case II is 11.4 feet (3.47 meters) and 15.1 feet (4.60 meters), respectively. However, only 1.4 feet (0.43 meter) of subsidence below present land surface would occur if artesian heads were maintained at their present levels."

SUMMARY #4

Land-Surface Subsidence in the Houston-Galveston Region, Texas, R. K. Gabrysch, C. W. Bonnet, U. S. Geological Survey, 1974.

Discussion:

This report is a regional report similar to the analyses and projections developed during the Burnett, Scott, and Crystal Bay Study. Data from Houston area wells and pumping records were gathered and analyzed, and regional projections were interpreted. Of significance is the estimation on the part of the authors that when artesian pressures are stabilized for an area, 80-85% of the ultimate subsidence in that area will have occurred.

Abstract:

"The pumping of large amounts of ground water in the Houston-Galveston region, Texas, has resulted in water level declines of as much as 200 feet (61 meters) in wells completed in the Chicot aquifer and as much as 325 feet (99 meters) in wells completed in the Evangeline aquifer during 1943-73. The maximum annual rates of decline for 1943-73 were 6.7 feet (2.0 meters) in the Chicot aquifer and 10.8 feet (3.3 meters) in the Evangeline aquifer. During 1964-73, the maximum rates were 10 feet (3.0 meters) in the Chicot and 17.8 feet (5.4 meters) in the Evangeline. The declines in artesian pressures have resulted in pronounced regional subsidence of the land surface.

"The center of subsidence is at Pasadena, where as much as 7.5 feet (2.3 meters) of subsidence occurred between 1943 and 1973. More than 1.0 feet (0.3 meter) of subsidence occurred at Pasadena between 1906 and 1943. The maximum amount of subsidence during 1964-73 was about 3.5 feet (1.1 meter).

"In the southern part of Harris County, about 55 percent of the subsidence is a result of compaction in the Chicot aquifer. The area in which subsidence is 1 foot (0.3 meter) or more has increased from about 350 square miles (906 square kilometers) in 1954 to about 2,500 square miles (6,475 square kilometers) in 1973.

"Estimates of subsidence are based on the amount of water-level decline, the thickness of the clay, and the compressibility of the clay. At Seabrook, it is estimated that for each 1 foot (0.3 meter) of average water-level decline, 1 foot (0.3 meter) of clay would compact 0.000031 foot (0.00094 centimeter). At Seabrook, for 1 foot (0.3 meter) of water-level decline, 0.0248 foot (0.756 centimeter) of subsidence would occur.

"Planned use of surface water instead of ground water will probably result in some recovery of artesian pressures. If pressure recovery occurs, the rate of subsidence should decrease substantially in the more critical areas."

SUMMARY #5

"Technological Limitations to Ground-Water Management", William F. Guyton, Presentation to Water for Texas Conference, TAMU, September, 1974.

Discussion:

This report presents the author's opinions on the development of the legal structures which control or may control groundwater use in the state. Basically, there has been little control to date. The developing control structures have taken the form of local underground water districts which do not deny production rights but initiate limitations on use. This reduction of absolute rights has taken the direction of a doctrine of correlative rights.

According to the author, there is now a movement to give to Texas Water Rights Commission authority to exercise groundwater control in any areas needing control. The author generally opposes government control of underground water but says there may not be a manageable alternative. He therefore suggests that the state's best effort be put forward to minimize problems and implement the best possible laws. This should probably include some type of protection of, or allowances for, the "grandfather" users in a controlled area and a system of water rights ownership based upon available supplies.

SUMMARY #6

Costs of Land Subsidence Due to Groundwater Withdrawal, John P. Warren, Lonnie L. Jones, et al, Texas Water Resources Institute, Texas A & M University, July, 1974.

Abstract:

"In recent years the area around Houston and Baytown, Texas, has been affected to an increasing degree by land subsidence. Sinking of the land surface has reached critical proportions in many areas, and subsidence of as much as eight feet has occurred. The severity of this phenomenon has been aggravated by the proximity of much of the affected area to bay waters, and tidal flooding has resulted in significant damages and property loss.

"Subsidence has been linked by engineers to the decline of subsurface water levels due to heavy groundwater withdrawals in the area. An alternative source for water demands has been introduced, although price differentials have slowed its acceptance.

"Major objectives of this study included estimation of historical costs attributable to subsidence, projecting estimated costs, and examining the economics of the two alternatives for water supply. A study area of 300 square miles was identified and sampling of residences, businesses, and public officials was carried out. The cost data resulting from those samples formed the basis for economic analysis.

"Historical costs and property losses that were attributable to subsidence were estimated to be $60.7 million and $48.9 million, respectively, or $109.6 million total. Of the $109.6 million, $53.2 million were incurred in 1973, principally due to a six foot tide. Probability of the occurrence of a six foot tide in any one year is 20 percent. Given five additional feet of subsidence in the study area, the occurrence of a six foot tide was projected to cause an estimated $63.5 million in costs and losses, $10.3 million more than were incurred in 1973.

"Estimated annual subsidence-related costs and losses of $14.6 million for the study area, based on 1969 to 1973 data, were used to evaluate total costs associated with supplying water needs from two alternative sources. A break-even analysis indicated that to minimize total water costs, pumping only that quantity of water that would result in no subsidence could be economically justified; i.e., water needs or demand above that rate would need to be purchased from an alternative source. This implied that when pumping is continued to the point that subsidence occurs, the cost of pumping plus associated subsidence-related costs and losses exceed water costs from an alternative source, per unit of water."

Summary & Conclusions:

According to this report, over 3000 square miles of the Greater Houston-Galveston area is experiencing subsidence to some degree. Approximately 300 square miles of that area were selected for this study, including 19 square miles identified as "industrial". Square mile units were categorized by elevation. Responses to questionnaires were used to identify subsidence-related damages and these damage estimates were then extrapolated to cover the entire study area. Subsidence damages totaled $60.67 million in private damages, $48.76 million in private property losses and $4 million in public property losses. Over $53 million of these damages resulted from a 6 foot tide in 1973. Since a 6 foot tide can be expected every 5 years, projections of losses were estimated assuming an additional two feet and five feet of subsidence. The projection resulted in estimated losses of $54.9 and $63.5 million respectively.

If the historic losses estimated in the study were included in the cost of groundwater use, the purchase of all of the areas' recent water needs (up to 132 billion gallons a year) from surface water sources would have been justified.

Several data limitations and their impacts were discussed. The fact that only 300 square miles had been studied because of time and money limitations was identified as a problem. Potential bias in the initial responses was identified as the largest single potential problem in the source data. Generally, the researchers concluded that their calculation of historical costs was low because of "conservative response evaluations", "an inability to accurately inflate costs to 1973 figures", and many respondents were not present at their location for the entire 30 year historical period.

In conclusion, the researchers suggested that the most pressing need for future research was the identification of the "maximum acceptable withdrawal rate" for the area.

SUMMARY #7

An Analysis of the Rate of Decline in Ground Water Level in the Area of Houston, Harris County, Texas. John G. Musgrove, Masters Thesis, University of Houston, December, 1973.

Abstract:

"A method of analyzing groundwater level declines (in order) to estimate a natural rate of groundwater recharge has been attempted. On the basis of observed water level annual rates of decline and the annual average daily rate of groundwater withdrawal, a rate of groundwater withdrawal associated with zero decline in the groundwater level may be determined.

"Correlation of the annual rate of groundwater level decline with the rate of groundwater withdrawal was made for six areas within the United States Geological Survey's Houston district as a whole. This correlation, by use of a least squares curve fitting of the data to generate a first order curve, produced negative and positive rates of natural recharge for the individual areas and produced a negative rate of natural recharge for the entire district. Correlation of the data with a more complex mathematical model will need to be done to accurately estimate the rate of natural recharge for the Houston district."

Conclusions and Recommendations:

The paper indicated that the linear model $AW(t) = p(t)-r$ (A - aquifer area; W(t) - water level decline rate; p(t) - volume pumped, r - natural recharge rate) is not sufficiently complex to represent the

natural rate of recharge for the Houston area. The paper concluded that the negative rate of recharge calculated indicates that variables were either not considered, or were assumed incorrectly.

The recommendations listed in the paper suggested that a more sophisticated model be developed. It also identified some of the variables which were not considered and which might have an impact on aquifer recharge in the original model. These included rainfall rate, rainwater runoff, and the variation in surface area available for recharge resulting from development.

SUMMARY #8

"Results of Land Survey of Houston-Galveston Area Announced; Land Sinking of 8 Feet Reported", Anonymous, U. S. Department of Commerce News Release, July 26, 1973.

Discussion:

This news release summarizes the results of National Oceanic and Atmospheric Administration study of subsidence in the Houston-Galveston area. The study, completed in 1973, contains tabular presentations of recorded subsidence at specific points since 1936. Twenty-nine points are listed in the Houston-Galveston area.

SUMMARY #9

"Sea Rising More Rapidly Along Texas and Louisiana Coasts; Land Sinking." Anonymous, U. S. Department of Commerce News Release, May, 1973.

Discussion:

NOAA scientists announced that the sea is rising faster along the Gulf Coast from Texas through Louisiana. Their findings were based on long term (1959-1971) tidal data as compared to earlier data.

The scientists were not agreed on whether this reflected land subsidence, rising oceans, or a combination of both. Changes in tide level from 0.2 to 1.5 feet were recorded.

SUMMARY #10

"Land-Surface Subsidence in the Texas Coastal Zone", W. L. Fisher, Presentation to the Council on Marine Related Affairs, February, 1973.

Discussion:

This report to the Texas Legislature summarizes and combines much of the research accomplished prior to 1973. The conclusions are presented below.

Conclusions:

"Withdrawal of ground water in the Houston-Galveston area has led to declines in piezometric levels; these declines have in turn resulted in dewatering and compaction of interbedded clay beds with an accompanying reduction in volume, expressed in subsidence of the land surface. Land surface subsidence is irreversible. It will continue at a progressively decreasing rate even if there is no further decline in piezometric levels. The amount of future subsidence will relate directly to the amount of piezometric decline."

SUMMARY #11

"How Much More Will Houston Sink? The Disturbing Problem of Land Subsidence", A. Frank Marshall, Jr., The Slide Rule, February, 1973.

Discussion:

This article, from which the summary below is reproduced, presents a synoptic non-technical appraisal of the history, causes, problems, potential problems, and needed actions related to subsidence in the Houston area.

Summary:

"Subsidence in the Houston region is continuing at an ever increasing rate and has reached 8 feet in the Pasadena-Deer Park area and 4-feet in the Clear Lake area. The location and the amount of subsidence are directly related to declines in groundwater level resulting from withdrawal of water from wells.

"By the year 2000, total subsidence is expected to reach 19 feet in the Pasadena-Deer Park area and 10 feet in the Clear Lake area. These estimates assume that water level declines will stop by 1980 which requires that by 1980 much of the water demand will be furnished by surface water. If the transition to surface water is delayed and water levels continue to decline after 1980, future subsidence will likely be more than that predicted. On the other hand, if a rapid shift to surface water by the major water users can be accomplished and the water levels are permitted to rise significantly, future subsidence can be reduced.

"The most significant consequence of subsidence is loss of elevation of lowlying areas adjacent to tidal waters. Many areas in Baytown, along the Houston Ship Channel and in the Clear Lake vicinity are now subject to flooding during high tides. Each increment of subsidence will enlarge the area subject to flooding.

"If future subsidence is to be minimized, major water users in the Pasadena, Baytown and Clear Lake areas must convert to surface water as soon as possible. With the completion of the CIWA system these areas can be adequately served by water from the Trinity River. It is hoped that the transition from groundwater to surface water can be accomplished through collective voluntary action; otherwise, state legislation will be needed to control groundwater withdrawals."

SUMMARY #12

"Inquiry on Land Subsidence and Wastewater Reuse", Citizens Environmental Coalition Education Fund, Incorporated, July 1972.

Discussion:

This six page "summary of major points" documented many of the recommendations and concerns of the public and of several experts in fields related to subsidence, water treatment and industrial water use. The summary generally documented the rates of subsidence and increasing rates of groundwater withdrawals. The report expressed the urgent need to reduce ground water demand by developing additional surface supplies, and encouraging municipal and industrial wastewater reuse.

The feasibility of municipal wastewater reuse was warranted by the proposed reuse of Clear Lake City municipal wastewater in the Bayport Industrial Complex, and by the contention that this municipal wastewater is of a higher quality than untreated Trinity River water. The report also suggests that injection of properly treated excess surface water at a rate of 800 MGD would be worth the costs in property loss prevention alone. The conclusions of this report are reproduced below.

Conclusion:

"That the problem of subsidence in the Houston-Galveston area is of major importance cannot be denied on the basis of material presented during the inquiry. The rate of subsidence will continue and increase if actions are not taken to reduce significantly ground water withdrawals. One major action to reduce ground water withdrawal would be to establish industrial and domestic reuse of treated waste water effluent as an alternative to the use of well water. A major disadvantage is in the area of costs: it is significantly more expensive to treat waste water than to use recognizably inexpensive and good well water. But the additional treatment costs will be more than returned in the benefits of protected and enhanced property values as well as general social benefits.

"Water tables in the area must be allowed to rise significantly -- not be stabilized where they are now--at perhaps up to 150 feet below where they were before any pumping was done. If action is taken only to maintain the water tables at present levels, residual subsidence could be one to one-and-one half times as great as current subsidence in twenty to thirty years. In addition to the reuse of adequately treated effluent and the increased use of available surface supplies, consideration should also be given to recharge of the water strata. On the basis of limited experience, recharge might cause subsidence to cease in about one year; treated effluent reuse and surface water use could prevent its recurrence."

SUMMARY #13

Groundwater Conditions in the Galveston Bay Area - Harris, Galveston, and Chambers Counties, Texas, William F. Guyton and Associates, Texas Water Quality Board, February, 1972.

Discussion:

This report was designed to determine the general availability of fresh groundwater in the study area and to estimate the effects on the piezometric surface of development of this groundwater. One section of the report summarizes the phenomenon of subsidence and its relationship to the declines in piezometric levels.

This report references a report by McClelland Engineers, Incorporated, which had projected that initial subsidence (occurring in direct association with piezometric declines) will be only 40 to 67% of the ultimate subsidence (occurring over a much longer time span).

This projection is somewhat contradictory to reports by Lockwood, Andrews and Newnam, Incorporated, and R. K. Gabrysch, et al, which projected that initial subsidence in association with piezometric declines is approximately 75% and 85%, respectively, of the ultimate subsidence.

The report also associated the recent activity of the longstanding coastwise faults with subsidence. The report suggests that this activity is "influenced by consolidation of clay" (i.e., subsidence).

The report identifies several potential problems associated with subsidence. These include protrusion of deeply-cased wells, pipeline breakage and clogging of sewer lines (presumably due to loss of gradient). However, the worst effects of subsidence identified by the report are coastal flooding and submergence in coastal lowlands.

SUMMARY #14

Land Surface Subsidence in the Houston-Galveston Region, Texas, Robert K. Gabrysch, Proceedings of the International Symposium on Land Subsidence, Tokyo, Japan, 1969 International Association of Scientific Hydrology, 1970.

Discussion:

This report is a presentation of known information concerning subsidence groundwater declines and area geology. The report contains no projections or quantitative relationship of groundwater withdrawals to subsidence. The report concludes that:

"Pumping and subsidence will increase until additional surface water is made available.

"After surface supplies are made available stabilization of the aquifer pressures may occur. Total subsidence will depend on the ultimate water-level decline which in turn is dependent upon the groundwater withdrawals.

SUMMARY #15

"San Jacinto Monument Warning of Future Land Subsidence", Mason G. Lockwood and H. P. Carothers, Southwest Water Works Journal, January, 1969.

Discussion:

This article concentrates on the possibility of secondary settling in the deep clays in response to increasing overburden pressure. This is not primary settling which in this report was defined as "loads slowly squeezing water out of the soil", but the slow differential movements of particles.

The article also stressed the importance of active surface faulting and the need to accurately define and plan around faults and fault zones. The report linked subsidence and fault activity by circumstantial evidence.

The report concluded with six suggestions for future need. They are:

"1. RE-LEVELLING PROGRAM. We must continue the regional re-levelling program. The next one is due in 1969, but it is not yet financed. This is the only reliable basis for knowing the amount of subsidence.

"2. MAP ACTIVE FAULTS. Prepare detailed maps of the active faults, and make these readily available so people can either avoid the faults or design to take the differential movements without serious damage.

"3. FORECAST LAND SUBSIDENCE. To start, make sophisticated soil borings (200 feet deep) and tests at the San Jacinto Monument as necessary to hindcast and forecast both primary and particularly secondary settlement in these Texas coastal clays. The monument is the only structure on these coastal soils with sufficient measured record of secondary settlement to permit this.

"Then, using the same techniques on the similar problems, make the necessary deep (over 1,500 feet) investigations as necessary to permit realistic hindcasts and forecasts of the regional ground subsidence under different water levels.

"4. FORECAST COASTAL FLOODING. Use Texas-size hurricanes - not just the customary average hurricane - to forecast and map in detail the probable future coastal flooding.

"5. PLAN NEEDED CONTROLS. Determine the amount and location of reduced pumping necessary to raise the water levels enough to stop the land subsidence in the critical areas subject to coastal flooding.

"6. GROUND WATER CONTROL. Find some means of responsibly controlling the pumping from wells and the ground water levels in the region. This will be a wildly controversial suggestion. I have trouble understanding the logic of a people who accept the essentiality of public control of oil and gas production and become virtually hysterical at the thought of any kind of effective public control of production of ground water."

SUMMARY #16

"Relation of Land Subsidence to Ground-Water Withdrawals In The Upper Gulf Coast Region, Texas", H. G. Winslow and Leonard A. Wood, Mining Engineering, October, 1959.

Discussion:

This 1959 report documents the existence of subsidence, and links it to groundwater withdrawals. This is accomplished by an elimination of other known processes causing subsidence and a reliance on circumstantial evidence showing the coincidental decline of artesian pressures and subsidence.

The report concludes that the potential effects of subsidence were lowland tidal and hurricane flooding, and structural damage to wells, pipelines, sewers, pavings, and foundations. The report estimated that subsidence would continue to occur for an indefinite period of time even if artesian pressure were stabilized because "the head in shallower sands will continue to decline as it adjusts to the lower heads of deeper sands." This statement indicates that at the time of this report the authors thought potential for vertical movement of water through formations (aquicludes) was possible.

SUMMARY #17

Earth Subsidence Forecast from Tests of Deep Soil Samples, H. P. Carothers and Frank H. Newnam, American Society of Chemical Engineers Spring Meeting Texas Section, Beaumont, Texas, May, 1958.

Discussion:

This report summarizes the research performed by Lockwood, Andrews and Newnam for the Jones and Laughlin Steel Corporation. Subsidence potential in the Cedar Point Area of Baytown was studied because the site was being considered for possible development.

The research concentrated on analyses of "Microlog" well logs from an on-site test water well to ascertain the depths and location of compactible clay layers. Ten undisturbed clay samples were collected and analyzed for liquid limit, plastic limit, moisture content, dry weight, and consolidation. These data were related to a variety of probable and possible water withdrawal forecasts for the site, and subsidence rates were projected.

The following conclusions were reached:

1. There had been very little recent subsidence in the Cedar Point Area; probably less than 0.3 feet.
2. Initial reduction of artesian pressures, perhaps 90 feet of decline, would not result in significant subsidence because of preconsolidation of the clays.
3. Ultimate subsidence caused by general groundwater withdrawals outside the Cedar Point area was estimated at approximately three feet.
4. Forecasts indicated that subsidence would occur in almost direct relation to declines in artesian pressure, with approximately 75% occurring initially, and approximately 25% occurring at a decreasing rate over many years.
5. Concentrated excessive pumping from the most attractive water bearing strata in the study site (Alta Loma and upper Lissie) would probably result in an isolated cone of subsidence of about 0.5 foot in the vicinity of the well field within a radius of 3,000 feet.
6. Excessive but improbable withdrawal from less attractive strata (shallow sands of the Beaumont Clay; i.e., low yield and quality) would probably cause serious isolated subsidence of up to 3.8 feet in a cone extending 3,000 to 5,000 feet from the well field.

The report was concluded with suggestions for the refinement of techniques. These included:

1. Thicker consolidation test samples should be used instead of the ultra thin samples used in this study. The thicker sample should give better definitions of preconsolidation and rate of consolidation.
2. Additional undisturbed clay samples collected in connection with well logging should add to the logging analysis and advance the subsidence projection technique.
3. Loads in the consolidation test should be carried well past the preconsolidation point to improve the definition of that point.

4. Further research is suggested to determine a satisfactory relation between liquid limit, void ratio, and compression.
5. Better basic data is needed to confirm the effectiveness of the assumed acquicludes in retaining the various aquifer declines at different levels.
6. This study assumed that the thin sand layers in clay as defined by the microlog would break the thickness of the clay for computing the rate of consolidation; i.e., the thin sand layers would drain the clays faster. However, more research is needed since these layers may be limited lenses which do not act to drain the clay layers.
7. Where the total amount of subsidence exceeds several feet, secondary subsidence (non-hydrodynamic compaction) becomes more important and there is a definite need to expand the long term subsidence predictive capability.

SUMMARY #18

"Land Surface Subsidence and its Relation to the Withdrawal of Ground Water in the Houston-Galveston Region, Texas", A. G. Winslow and W. W. Doyal, Economic Geology, Volume 49, No. 4, 1954.

Discussion:

This report characterizes the state of knowledge of subsidence in the early 50's and the general lack of concern for the potential adverse impacts. The only mention in this report of any negative effect of subsidence was a reference to the loss of some pasture land known as the Gaillard Peninsula due to tidal flooding. The abstract and summary reproduced below address the author's interest in increased water production and "overall performance of the aquifer".

Abstract:

"Leveling by the United States Coast and Geodetic Survey in 1951 showed a general land-surface subsidence in the Houston-Galveston region, Texas, since previous leveling in 1943. The region of subsidence coincides with a region of a large-scale ground-water withdrawals where the water is pumped from a series of unconsolidated sands interbedded with clay layers. In the northern part of the region the

ratio of land-surface subsidence to decline in artesian pressure head is about 1 to 100. In the southern part of the region, where there is a greater percentage of clay in the section, the ratio is greater. The subsidence is attributed to compaction of the clays as the artesian pressure in the sands is reduced. From a comparison of the volume of subsidence to the volume of water pumped, it appears that about one-sixth of the water pumped has been supplied from storage in the clays."

Summary:

"The releveling of 1951 shows a general land-surface subsidence of considerable magnitude in the Houston-Galveston region corresponding generally in area and depth to the cone of depression by the removal of ground water. The actual volume of the subsidence, and hence the volume of water released by compaction, cannot be computed accurately because level lines in the Houston Ship-Channel area were not releveled. If the amount of subsidence in the Ship-Channel area were determined, a reasonably accurate value for the total volume of subsidence in the region might be computed. However, 2 years has elapsed since the releveling of 1951, and additional subsidence has undoubtedly occurred. It might, therefore, be necessary to relevel the entire net in the region in order to obtain satisfactory ties to bench marks in areas where there has been no subsidence. Inasmuch as a considerable part of the ground water withdrawn in the area appears to have been supplied by compaction, a periodic releveling throughout the region would be desirable. Correlating the data thus obtained with the geology and ground-water withdrawals in the region would result in a much better estimate of the overall performance of the aquifer."

SUMMARY #19

"Subsidence from Declining Artesian Pressure Can No Longer Be Ignored in Houston Area, Texas", Mason G. Lockwood, presented at the Spring Meeting, Texas Section ASCE, April 9, 1954.

Discussion:

This report is a synopsis of known subsidence information in 1954. It does not quantitatively analyze or project subsidence but does present estimates of the problem and its consequences. There are several conclusions presented in the paper which are reproduced below.

Conclusions:

"1. The heavy withdrawal of confined ground water for municipal and industrial use in the Houston, Texas area has caused a cone of pressure relief, or decline in artesian pressure over most of Harris County, due to concentrated pumping. This decline has been accompanied by a remarkably similar conical depression of the ground surface, in the approximate order of one foot per one hundred feet of decline in artesian pressure head.

"2. Analysis and interpretation of available information on this complex subsidence, by authorities on soil mechanics and geology, indicates that it is largely due to consolidation of the soil arising from reduction in artesian water pressure. To some extent, however, it probably is due in portions of the area to the superposition of subsidence from declining gas pressure, or related hydrostatic pressure, in the oil fields.

"3. The maximum relative subsidence between Lake Houston Dam and the center of the industrial district on the south side of the Ship Channel is about 3.25 feet. The area in the vicinity of the dam probably has sunk, however, about 0.3 to 0.5 feet to date, based on a study of the contours and profiles of the general subsidence and decline of artesian pressure. Therefore, it is concluded that the total subsidence to date in the Pasadena area is a maximum of from 3.5 to 3.75 feet. This is in the area of maximum pressure decline shown on Figure 4.

"4. The artesian pressure in the Pasadena area is declining at the rate of about 100 feet in 8 years. At that rate, the pressure level will have fallen to about minus 450 feet before 1970. That is the approximate elevation of the top of the major aquifer in a representative well in the area. Thus, there is reason to believe that within the next fifteen years the earth's surface in the region of maximum disturbance, will have subsided twice as much or more than it has to date. This estimate of future subsidence compares reasonably well with a theoretical determination made by a rather oversimplified consolidation analysis which necessarily employed assumed values for the mechanical properties of the soils.

"5. The ground elevation loss is permanent. There could be little rebound, even with conceivable but wholly improbable restoration of original artesian pressure. Actually, at any given time, the subsidence can be halted only by an increase in artesian pressure.

"6. Known or suspected subsidence-induced difficulties in the Houston area, relatively speaking, have not been very serious to date. Fortunately, the major faults have not occurred in areas occupied by important structures. There has been minor differential settlements resulting in cracking of building walls. Revision of plans for canals, roads, and drainage systems have been made necessary by the subsidence. The loss of ground elevation in areas of maximum subsidence already has wiped out the normal freeboard allowance for flood and hurricane tides. Much confusion and expense in running and maintaining differential levels is directly due to subsidence. Probably, more often than not, however, the trouble has been attributed erroneously to some other factor.

"J. R. Sims points out a curiously interesting coincidence arising from the fact that in the subsiding area under discussion, was situated the starting point used by the U. S. Coast and Geodetic Survey for computing the elevations of all other junction points in the 1927 national level net, and subsequently the 1929 adjustment which included Canada.

"After the 1927 Special Adjustment net - to quote from official report of the U.S.C. & G.S. -

> '...had been made entirely consistent within itself by the adjustment, the unadjusted difference of elevation between mean sea level at Galveston, Texas, and the junction bench mark at Houston, Texas, was used to determine the elevation of the junction bench mark at Houston. From that starting point the elevations of all other junction points in the net were computed.'

"Then in the 1929 Special and General Adjustments -

> '...as in the 1927 Special Adjustments, elevations based on Galveston, Texas, were computed for the mean-sea-level planes at the other tide stations.'

"The value of the key bench mark in Houston is obviously destroyed. Also, it would seem that the important tide gage at Galveston is close enough to the subsiding areas in Houston and Texas City to warrant the most careful consideration of the future validity of the Galveston gage.

"7. More serious troubles may be expected in the future if this subsidence continues at the present rate or increases. Up to now, neither uniform nor differential subsidence has received much, if any, detailed consideration by designers and builders. The time has come for responsible management to have its planners, designers and constructors recognize the significance of the subsidence factor in all its important future undertakings in the affected area.

"8. More care should be exercised hereafter in placing wells adjacent to concentrated industrial or other high-value developments, buildings, wharves or other structures. Especially, if the wells are of such depth and in soil conditions that might cause abrupt local cones of subsidence.

New buildings either should be located clear of known surface fault lines or be designed for differential settlement. Elevated tanks ought not to be located too close to wells producing from shallow depths. Where differentials or tilting would appear to be prospect, special care should be taken in the design and routing of surface drainage, sewers, water and other underground utilities.

"9. To cope with this subsidence problem, there must be a reduction in the excessive rates of withdrawal of ground water in the critical area. This would entail dispersion of well fields and much increased use of river water in the future.

"10. Ample sources of good water are available for all foreseeable future municipal and industrial requirements of the Houston Area. Supplies, entirely satisfactory in quantity and quality, can be developed at reasonable costs from ground and river sources, in such a way as to minimize the subsidence pitfalls of the future. The incremental cost of transmission to heavily developed areas, from properly situated well fields and from rivers, might prove to be less in the long run than the unhappy alternate serious property damages in the subsiding area.

"11. What is needed now, is more information, more data,more study and more technical and lay interest in and discussion of this subject. Frequent and complete coverage of the subsiding area by precise levels, is very desirable. The U.S.C. & G.S., which is now releveling along the Houston Ship Channel, and all other agencies public and private, should release significant data bearing on the situation as early as is feasible. In addition to precision leveling records, it would be helpful to have any good detail maps showing traces of identifiable old and new faults in the area.

"Consolidation tests should be made, perhaps as a community enterprise, on the typical clays, sandy clays and silty sands of each formation involved in the water wells. Electrical micrologs should be run on typical wells. Reservoir pressure measurements at peak production, and in the various aquifers, should be made. All of this, in order to afford a basis for really dependable estimates of future rates and ultimate amounts of subsidence; and, to assist in forecasting possibilities of abrupt and destructive differentials.

"12. Finally, this paper is, and must be recognized as, merely a preliminary report on the subsidence situation of the Houston Area. Of necessity, it is based on technical data too meager and

too incomplete for more specific evaluation of the ultimate consequences. Such conclusions as have been reached, were possible only by the most dogged and determined gathering and interpretation of the scattered information on the subject and by the extraordinary professional assistance and friendly cooperation of an unusually large number of engineers and geologists. To recite the polite acknowledgements customarily found in technical writings, would be to miss the main point here. Better, perhaps, to say that the work of these contributors is both a practical application and a heartening manifestation of the spirit of the very first Commandment of the 'Canons of Ethics for Engineers' which states that:

> 'The engineer will cooperate in extending the effectiveness of the engineering profession by interchanging information and experience with other engineers and students and by contributing to the work of engineering societies, schools, and the scientific and engineering press.'

SUMMARY #20

"Ground Waters of the Houston-Galveston Area", Margret D. Foster, Industrial and Engineering Chemistry, Volume 31, No. 6, August, 1939.

Discussion:

This 1939 report discusses the water formations and groundwater characteristics of the Houston area known at that time. The report contains a chapter on loss of artesian head pressure in the aquifer but the author does not discuss subsidence as a possible problem associated with continuing groundwater development. There is a significant amount of discussion on salt water intrusion as a problem associated with declining head pressures. The report also includes recommendations to minimize salt water intrusion by dispersing major producing wells.

Because of the discussion on salt water intrusion, it is reasonable to assume that subsidence, even if known at that time, was not considered a problem associated with groundwater withdrawal.

C. RECENTLY IDENTIFIED STUDIES

Four reports were identified late in the subsidence project and some were used as references in the narrative discussions of the report. They were not formally reviewed and summarized, however, because of time constraints in the project. These documents may provide additional information for subsequent research.

1. Anonymous, Research Report 1, Texas Gulf Coast Program, Rice Center for Community Design, 1976.
2. Brown, L. F. Jr., et al, Natural Hazards of the Texas Coastal Zone, University of Texas, Bureau of Economic Geology, 1974.
3. Sheets, Martin M., "Active Surface Faulting in the Houston Area", Houston Geological Society Bulletin, Vol. 13, No. 7.
4. Sheets, Martin M., "Subsidence, Active Surface Fault and Project Location", Society of Independent Professional Earth Scientists, Bulletin No. 9, 1974.
5. Jorgenson, Donald D., Analog-Model Studies of Groundwater Hydrology in the Houston District, Texas, U. S. Geological Survey, February, 1975.
6. Gabrysch, R. K., and C. W. Bonnet, Land-Surface Subsidence at Seabrook, Texas, USGS Water Resources Investigation No. 76-31 (In Press).
7. Gabrysch, R. K. and C. W. Bonnet, Land-Surface Subsidence in the Area of Moses Lake Near Texas City, Texas, USGS Water Resources Investigation No. 76-32, (In Press).
8. Anonymous, Harris-Galveston Coastal Subsidence District, District Plan, July, 1976.
9. Krietler, C.W., Lineations and Faults in the Texas Coastal Zone, University of Texas at Austin, Bureau of Economic Geology, 1976.

PART VIII - GLOSSARY

1. Artesian level (pressure) - Underground water pressure; in this case the level to which water will rise under its own pressure in a well completed in an aquifer.

2. Aquiclude - An impervious geologic stratum which separates aquifers.

3. Aquifer - A water-bearing stratum of permeable rock, gravel or sand.

4. Cone of subsidence (depression) - A circular area of depression created if subsidence occurs across an exactly level area. In reality, the topography of the 208 area is more convoluted than the subsidence which has occurred. The "cone" is an abstract reference which identifies the roughly circular area within which subsidence has occurred to a greater and greater degree towards the center.

5. Correlative Right - Having a mutual or reciprocal relation in such a sense that the existence of one necessarily implies the existence of the other.

6. Differential subsidence - a) The difference in subsidence recorded from one point to another. b) An isolated cone of subsidence which sometimes occurs in the near vicinity (within 1 mile) of a high volume producing well.

7. Extensometer - An instrument for measuring minute deformations (compression) of test materials (clays).

8. F.W.S.D. - Fresh Water Supply District. A political subdivision within the State of Texas which provides sewer utility service within its jurisdiction.

9. Geomorphology (geomorphic adjective) - The study of land and submarine relief features and processes.

10. Grandfather users - Entities with rights exempted from, or accounted for, in subsequent controlling legislation.

11. Groundwater - Water in the earth which supplies wells or springs.

12. Groundwater level - Artesian level; in this case the level to which water will rise under its own pressure in a well completed in an aquifer.

13. Hydrostatic pressure - Artesian pressure; in this case the natural pressure in an aquifer which will raise water to a certain level in a well completed in that aquifer.

14. Inflow/Infiltration - In this case, the influx and permeation of water into a municipal sewage collection system.

15. Isobar - An imaginary line or line on a map connecting equivalent points. Synonym - contour.

16. Leveling (re-leveling) - To survey the topography of a geographic area.

17. Liquid limit - The water content of a soil (expressed in % dry weight) having a consistency such that two sections of soil separated by a groove will touch but not flow together under the impact of several sharp blows.

18. Micro-log - Well logging technique which measures relative electrical resistance in strata. The technique has the advantage of producing high "resolution" logs of the geologic strata but is susceptible to interferences.

19. Model - A mathematical description in the form of equation(s) which characterizes a phenomenon or process.

20. Piezometer - An instrument for measurement of the pressure change in a material subjected to hydrostatic pressure.

21. Preconsolidation (of clays) - That "natural" consolidation or compression of the clay strata which occurred prior to the modern (since 1900) phenomenon of subsidence.

22. Pressure transducer - An instrument which measures and records changes in pressure (compression).

23. Recharge (aquifer recharge) - To restore water to an aquifer usually by percolation of surface waters through permeable strata.

24. Recharge area - An area where a permeable stratum outcrops and surface waters are allowed to percolate underground.

25. Secondary settling (... effects, ... compression, ... subsidence) - Non-hydrodynamic compaction of clays, or compaction which occurs as the result of differential particle movement and not in response to water displacement.

26. Static water level - Artesian level; in this case, the level to which water will rise under its own pressure in a well completed in an aquifer.

27. Subsidence - The sinking of the land surface.

28. Tidal flooding - Flooding which occurs as a result of wind-driven tides in coastal areas and not due to rising runoff water resultant from heavy rains.

29. Topography - The configuration of the land surface.

30. W.C.I.D. - Water Control and Improvement District. A political subdivision within the State of Texas which provides sewer utility service within its jurisdictional area.

31. Well logs - A graph indicating geologic strata. The log is obtained by measuring the relative electrical or acoustical properties of strata and estimating their densities.